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The Improvement in Performance a Ground Combat Vehicle Could Expect From the Use of a Real Time MET Sensor.

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14. ABSTRACT
The work presented within suggests new input values for the air temperature and air density portions of an error budget. It then uses those values to compare the performance of several strategies for entering meteorological data into a fire control system. This is accomplished by first defining the expected variation in air temperature and density for an engagement scenario and then using this information to find a standard error that a fire control system would be subject to based on the input strategy chosen. The results show that a real time meteorological sensor would significantly reduce the errors in round delivery that come from air temperature and moderately reduce the errors originating from air density.

15. SUBJECT TERMS
MET Sensor, Meteorological Sensor, Fire Control System Performance, Error Budget

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Contents

Introduction

In the recent years, several battle hardened real-time meteorological sensors have become available on the commercial market. These sensors can be mounted on a combat vehicle and be used to measure air temperature, air pressure, and humidity. This information can then be used by the vehicle's fire control systems to deliver projectiles to their intended targets more accurately. To quantify the gain in delivery accuracy a ground combat vehicle can expect from the use of a real time meteorological (MET) sensor, MET data is obtained for the intended operating environment, the data is interpreted for the fire control system, and metrics are calculated that describe the expected error associated with each approach.

Background:

A projectile's trajectory is sensitive to atmospheric conditions such as air temperature and air density. These two components have a known influence on a round being fired downrange and therefore their effects can be mitigated by the fire control system. In order to do so, the fire control system needs to acquire data about the local air temperature and density. From this data, corrections to the weapon pointing angle can be made to compensate for the influence the environmental conditions would have on the flight path of the projectile. The method the fire control system uses to acquire MET data will determine how much of the atmospheric effects can be accounted for. The current practice is to manually enter the average daily air temperature and air density for the mission location into the fire control system (FCS). While this approach does reduce a large portion of the error, there is still improvement to be gained through more accurate methods. Some combat vehicles enter the average value for both parameters more frequently (twice a day) to improve performance. However, a more accurate and convenient alternative is to use a sensor that collects data in real time and feeds it directly into the fire control system. In this study, metrics that describe the accuracy of each approach are found and used to compare the three methodologies.

Process

The process used to evaluate the MET data acquisition methods consists of three parts. First, MET data is obtained for the intended operating environment. The data is then interpreted for the fire control system taking sensor limitations into account. Finally, statics are calculated that can be used for direct comparison of the three methodologies or in an error budget to calculate down range miss distances.

Data Collection & Processing:

In order to obtain meaningful results, air temperature and air density data with multiple readings in a 24 hour time span is needed. With this data, the FCS values can be compared to the corresponding truth values to determine the error in each component over the course of a day. A good source for MET data is: http://www.worldweatheronline.com as readings are available in 3 hour increments over several years at various locations throughout the world. For the results presented within, data was obtained from the weather station in Kabul, Afghanistan for every Monday between 2008 and 2012.

A sample line of data looks like:

		1:30	4:30	7:30	10:30	13:30	16:30	19:30	22:30
7/7/2008	Time	1:30	4:30	7:30	10:30	13:30	16:30	19:30	22:30
	Air Temp (F)	61	57	69	89	93	90	76	64
	Humidity (%)	27	30	21	13	10	10	17	22
	Air Pressure (mb)	1007	1007	1007	1003	1002	1000	1005	1007

Table 1: Sample MET Data

The data set in Table 1 shows the meteorological parameters recorded by standard weather equipment, which includes weather stations and MET sensors. This sample shows that direct measurements are available for air temperature but not for air density. Therefore, air density needs to be derived from the available data.

Air in the first layer of the atmosphere can be considered a mechanical mixture composed of gas constituents, water vapor, and particulates. The density of dry air is about 1.2 kg/m^3, water vapor is 0.03 kg/m^3, and particulates are around 1.5x10^{-7} kg/m^3. From the magnitudes of these values, it is safe to assume that only the weight of dry air and water vapor is relevant to the total density of air. This can be then be expressed as:

$$D_{air} = D_{dry\ air} + D_{water\ vapor} \qquad \text{EQ.1}$$

The density of each part In EQ. 1 can be expressed as:

$$D = \frac{p}{R_s T} \qquad \text{EQ.2}$$

And therefore

$$D_{air} = \frac{p_d}{R_{s_d} T} + \frac{p_v}{R_{s_v} T} \qquad \text{EQ.3}$$

EQ. 3 shows that the density of the air is depended on how much water vapor is in the air. To find this quantity, the relative humidity can be used. Relative humidity is a ratio of how much water vapor the air is holding to how much it can hold. This is equivalent to ratio of the partial pressure of water vapor to the saturated pressure of water vapor.

$$Relative\ Humidity\ (\%) = \frac{p_v}{p_{saturated}} \qquad \text{EQ.4}$$

Relative humidity is a parameter recorded by the MET sensor and $p_{saturated}$ is a known value that has been measured for a discrete collection of temperatures. Since the temperatures in the obtained data set will not match the temperatures $p_{saturated}$ was recorded at, a polynomial equation can be used to estimate $p_{saturated}$:

$$p_{saturated} = \frac{p_{so}}{{p_e}^8} \qquad \text{EQ.5}$$

Where

$$p_e = c0 + T_C\left(c1 + T_C\left(c2 + T_C\left(c3 + T_C\left(c4 + T_C\left(c5 + T_C\left(c6 + T_C\left(c7 + T_C\left(c8 + T_C(c9)\right)\right)\right)\right)\right)\right)\right)\right)$$

EQ. 5 is less known than the Goff Gratch equation, but it is applicable in a similar temperature range and is easier to implement. To confirm the correctness of EQ.5, the following chart shows the error in the calculated values compared to the known values for saturation pressure of water vapor.

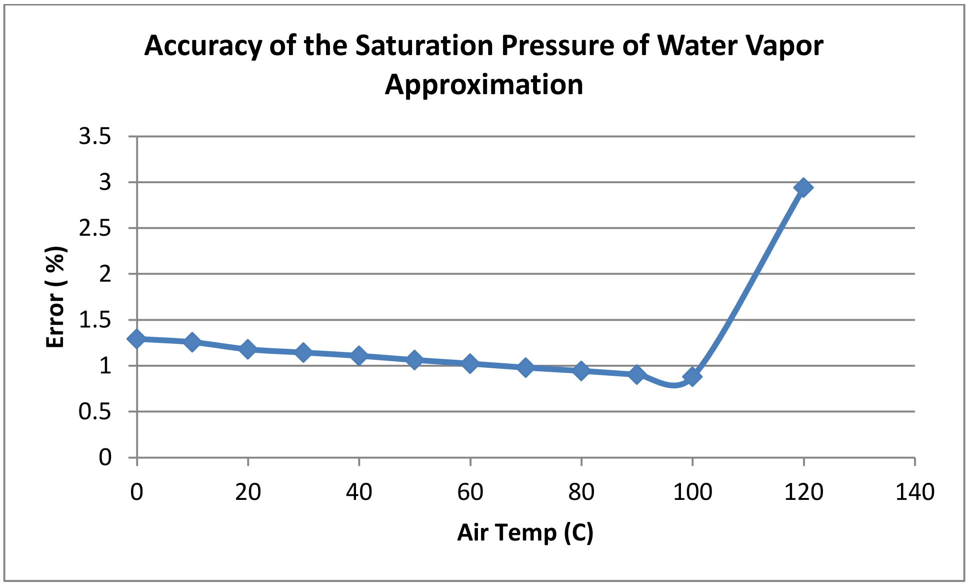

Fig. 1

Fig. 1 shows that the approximation for $p_{saturated}$ show in EQ.5 is valid for air temperatures up to 100 deg C. This is well within the limits of the acquired data.

Before calculating air destiny, the recorded air pressure needs to be back corrected for altitude. This is because the recorded value in the data set is what the sea level pressure would be if the weather station was at sea level. This is done in weather data intended for a general audience because it makes it easier to compare air pressures in regions with different altitudes. In order to get the local air pressure that the FCS would be subject to, the following equation is used:

$$p_l = p_b * \left(\frac{T_{m,b}}{T_{m,b} + L_{m,b}(H - H_b)}\right)^{\frac{g*M}{R*L_{m,b}}} \qquad \text{EQ.6}$$

Table 2 shows a comparison of the two values for a sample line of data.

		Corrected Air Pressure Readings (mb)							
7/7/2008	Time	1:30	4:30	7:30	10:30	13:30	16:30	19:30	22:30
	Recoded Pressure (mb)	1007	1007	1007	1003	1002	1000	1005	1007
	Corrected Pressure (mb)	811	811	811	808	807	805	809	811

Table 2: Sample Corrected Air Pressure

It is important to note that the corrected air pressure values are in the same range as the NOAA recorded values at the Kabul weather station.

The next step is to rearrange EQ. 4 to obtain

$$p_v = Relative\ Humidity\ (dec) * p_{saturated} \qquad \text{EQ.7}$$

Since p_v can now be calculated, the only unknown value in EQ. 3 is p_d. However, knowing that

$$p_l = p_d + p_v \qquad \text{EQ.8}$$

p_d can be easily obtained through EQ.6 and EQ.7.

$$p_d = p_l - p_v \qquad \text{EQ.9}$$

Now that all variables in EQ. 3 can be found, the equation can be used to calculate the air density. Replacing the humidity and air pressure data in Table 1 with the results of EQ.3 yields the desired data set. Table 3 shows an example of this.

7/7/2008	Time	1:30	4:30	7:30	10:30	13:30	16:30	19:30	22:30
	Air Temp (F)	61	57	69	89	93	90	76	64
	Density (kg/m^3)	0.9744	0.9821	0.9596	0.9205	0.9133	0.9167	0.9451	0.9691

Table 3: Sample Air Temperature and Density

Sensor Input Simulation

The interpretation of the MET data from a FCS perspective depends on the methodology used to enter the data into the fire control system. The three methodologies considered are: Daily Average, 2x Daily Average, and Real Time MET Sensor.

In the Daily Average approach, data is verbally communicated (called in) to the crew operating the weapon system on a daily basis. A crew member enters the value into the fire control system through a key pad and the value is used until a new value arrives. The 2x Daily Average approach works the same way, but the data is called in twice; once in the morning and once in the afternoon. In the Real Time MET Sensor approach, data is collected at the vehicle using a dynamic MET sensor that feeds the information directly into the fire control system. The sensor, however, is assumed to be imperfect and is given limitations in the accuracy of its readings of each parameter. These limitations are based on a survey of available MET sensors currently on the market.

To obtain the values for each approach, the following is used:

$$1x\ Daily\ Value(t) = \frac{1}{n}\sum_{i=1}^{n} v(i) \qquad \text{EQ.9}$$

$$2x\ Daily\ Value(t) = \begin{cases} \frac{1}{n/2}\sum_{i=1}^{n/2} v(i), & 0 \le t < 12 \\ \frac{1}{n/2}\sum_{i=\frac{n}{2}+1}^{n} v(i), & 12 \le t < 24 \end{cases} \qquad \text{EQ.10}$$

$$MET\ Value(t) = v(t) + Error(\mu_s, \sigma_s) \qquad \text{EQ.11}$$

From this, if the FCS requests the MET data at time t in a 24 hour period, the above equations describe how the return value is calculated based on each approach. EQ.9 returns the average value at any time t. EQ. 10 returns the average of the first half of the day if the requested time is in the first half of the 24 hour period and the average of the second half of the day if the request time is in the second half of the day. EQ. 11 returns the value at time t but with some error. In EQ.11, if the request is for air temperature, the error will come from the sensor's inaccuracy in reading air temperature. If the request is for air density, the error will be a combination of inaccuracies in reading air temperature, relative humidity, and air pressure as those values are needed to compute air density. The $Error(\mu_s, \sigma_s)$ value in EQ. 11 comes from the sensor specifications. It is assumed that the inaccuracy in the sensor's reading is normally distributed and the error tolerance given in the sensor literature is the 3σ value with a mean of 0.

Applying EQ. 9, EQ. 10, and EQ. 11 to the sample data produces:

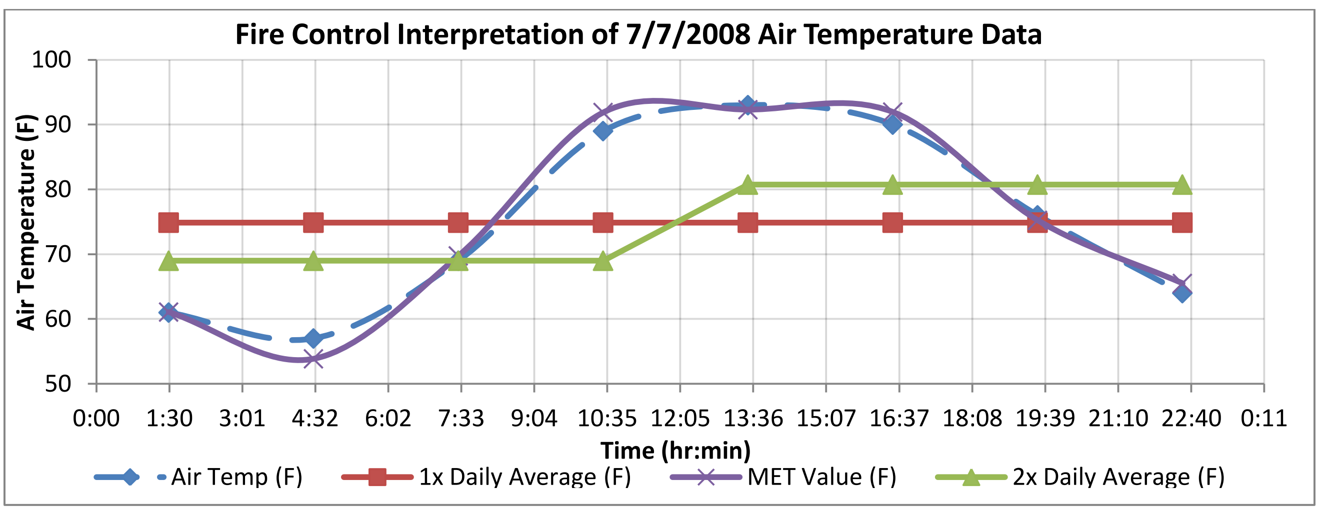

Fig. 2

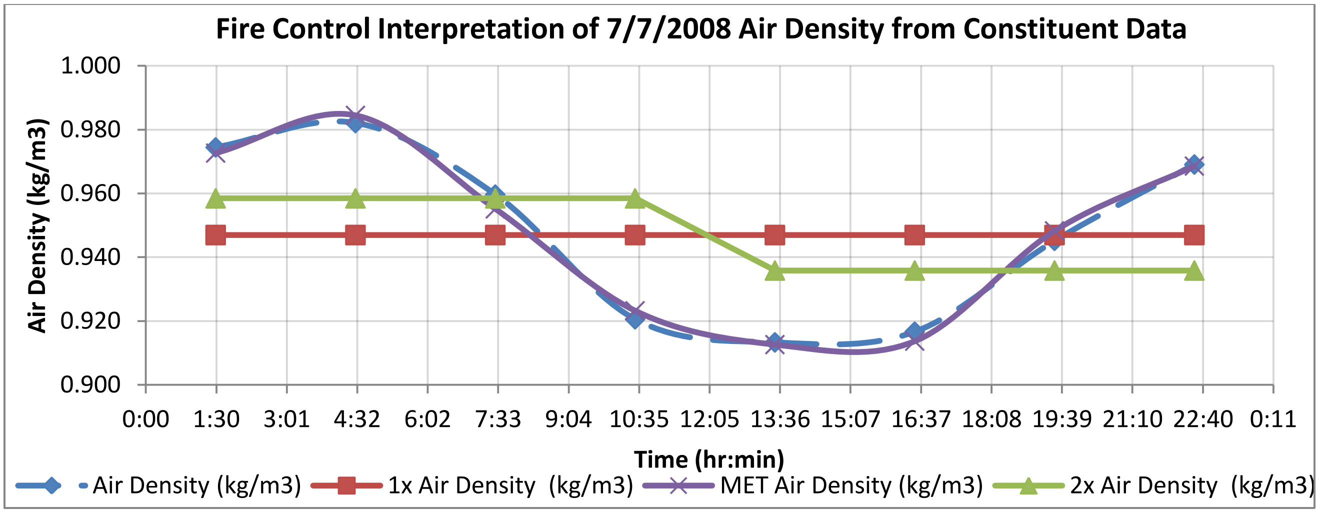

Fig. 3

Fig.2 and Fig.3 show how each recorded MET value varies in a 24 hour period and how closely each approach represents the true value.

To make this data more meaningful from a FCS perspective, the error value needs to be converted to a percent error. Doing this allows for the use of Unit Effects Tables to find the displacement of a round from its intended target due to a given MET condition. It also makes it easier to use the error values in an error budget to see how the changes influence the weapon system as a whole.

Converting the absolute air temperature and air density errors to absolute percent error for the 7/7/2008 data sample yields:

	Air Temperature Error (%)							
Time	1:30	4:30	7:30	10:30	13:30	16:30	19:30	22:30
1x Daily Average (%)	2.7	3.5	1.1	2.6	3.3	2.8	0.2	2.1
2x Daily Average (%)	1.5	2.3	0.0	3.6	2.2	1.7	0.9	3.2
MET Value (%)	0.0	0.6	0.1	0.5	0.1	0.4	0.1	0.3

Table 4: Air Temperature Error (%)

	Air Density Error (%)							
Time	1:30	4:30	7:30	10:30	13:30	16:30	19:30	22:30
1x Daily Average (%)	2.8	3.6	1.3	2.9	3.7	3.3	0.2	2.3
2x Daily Average (%)	1.6	2.4	0.1	4.1	2.5	2.1	1.0	3.4
MET Value (%)	0.2	0.2	0.5	0.3	0.1	0.3	0.3	0.0

Table 5: Air Density Error (%)

Data Statistics

In cases where generalizations need to be made about the expected errors, such as when calculating an error budget, it is more meaningful to use a distribution function to represent the errors rather than the actual error values. It most cases, the error values are represented by a normal distribution with a mean value of 0 and a given standard deviation. The mean is usually 0 because most FCS systems have a functionality to eliminate constant errors. This makes the standard deviation the parameter of interest.

For air temperature, obtaining the standard deviation for the 1x Daily Value and 2x Daily Value approaches is straight forward. The percent error at each data point is calculated and then the standard deviation of the results is found. For air temperature using the MET Value approach, a different strategy is used since the MET sensor is will have a random error at each data point. Monte Carlo simulation is used along with the sample data to produce this statistic. To obtain the presented value, 1000 iterations were used. At each iteration, a random error based on the sensor specification was introduced at every data point. Then, the standard deviation for the error in the data set is calculated and maintained. The standard deviations are then averaged together to produce a final value. This may seem unnecessary as the 1σ value for air temperature will be the 1σ value of the accuracy of the sensor's reading. This is true for air temperature, but this process becomes necessary for the calculating the standard deviation for the air density error using the MET Sensor approach.

The standard deviation of the air density error is somewhat more difficult to find as the value is a result of the error in the air temperature, relative humidity, and atmospheric pressure readings. To find this statistic for the 1x Daily Value and 2x Daily Value approaches, the air density is calculated using the values the FCS would see for each constituent piece of data. Then, the percent error is found for each point in the data set and the standard deviation is calculated. For the MET Value approach, a similar method to the air temperature MET Value approach is used. However, rather than introducing an error into the air temperature reading only, random errors are introduced into the humidity and atmospheric pressure values as well. Then the imperfect values are used to calculate the air density a FCS would use. The values are then compared to the correct values to determine a percent error. This is done for 1000 iterations and the standard deviations in the error are averaged to produce the final value.

The results of doing this are:

Air Temperature Error Standard Deviation

Method	1σ Error (%)
1x Daily Value	2.01
2x Daily Value	1.73
MET Sensor Value	0.12

Table 6: Air Temperature Error Standard Deviation

Air Density Error Standard Deviation

Method	1σ Error (%)
1x Daily Value	2.20
2x Daily Value	1.88
MET Sensor Value	1.03

Table 7: Air Density Error Standard Deviation

Results

The results obtained within offer error values to use for each MET acquisition strategy to describe the accuracy of the method. The presented values are reasonable when compared to previous work. The standard deviation values for air temperature and air density errors presented in Table 6 and Table 7 are close to the commonly used values of 1.5% for each parameter. Those common values are based on engineering estimates made by subject matter experts. Therefore, the presented values need not match perfectly as they are based on a particular data set. However, since the 1x Daily Value Approach and the 2x Daily Value Approach closely resemble the current methodology for compensating for air temperature and air density, it makes sense that the calculated values are similar to the engineering estimates. It is also reasonable that the MET Sensor approach standard deviation error values are smaller than the values used in the manual entry methods. This is because the values obtained by the MET sensor, even with the errors for each parameter reading, are closer to the actual conditions than the 1x and 2x Daily Average methods. This can be seen clearly in Fig. 2 and Fig. 3. The MET sensor air density error value is slightly higher than that of the air temperature because 3 measurement inaccuracies are contained with that value compared to the 1 measurement inaccuracy for air temperature. If the MET sensor was able to measure the air density directly, its error value would improve. Overall, the results agree with the generally accepted values for weapon platforms using manual entry to convey MET data to the FCS and the newly developed error values for weapon systems using dynamic MET sensors are reasonable.

Conclusions

The presented work examined several methodologies for communicating meteorological data to the FCS in order to improve round delivery accuracy. This was done through a 3 step process. First, MET data was obtained for the intended operating environment. Then the MET data was interpreted for the FCS using a 1x Daily Average approach, a 2x Daily Average approach, and a Dynamic MET Sensor approach. Finally, the errors in the air temperature and air density values were calculated and the standard deviations associated with each approach were found. The results showed that the values obtained for 1x and 2x Daily Value approaches were similar to the currently used values. Additionally, the results showed that entering the data more frequently using manual entry methods provided minor improvements. The MET Sensor Approach showed significant improvements in the air temperature error and moderate improvements in the air density error. From this, the conclusion can be made the any FCS using the 1x or 2x Daily Average approach would benefit from upgrading to the MET Sensor approach.

Symbols

Symbol	Description	Value	Units
D	density	-	kg/m^3
D_{air}	density or air	-	kg/m^3
$D_{dry\ air}$	density of dry air	-	kg/m^3
$D_{water\ vapor}$	density of water vapor	-	kg/m^3
p	atmospheric pressure	-	mb
p_l	local (back corrected) atmospheric pressure	-	mb
R_s	specific gas constant	-	J/(kg*degK)
T	temperature	-	K
p_d	atmospheric pressure due to dry air	-	mb
p_v	atmospheric pressure due to water vapor	-	mb
R_{s_d}	gas constant for dry air,	287.05	J/(kg*degK)
R_{s_v}	gas constant for water vapor	461.495	J/(kg*degK)
$p_{saturated}$	saturation vapor pressure	-	mb
p_{so}	constant	6.1078	-
p_e	pressure estimation scaling constant	-	-
c0	constant	0.99999683	-
c1	constant	-0.90826951*10^{-2}	-
c2	constant	0.78736169*10^{-4}	-
c3	constant	-0.61117958*10^{-6}	-
c4	constant	0.43884187*10^{-8}	-
c5	constant	-0.29883885*10^{-10}	-
c6	constant	0.21874425*10^{-12}	-
c7	constant	-0.17892321*10^{-14}	-
c8	constant	0.11112018*10^{-16}	-
c9	constant	-0.30994571*10^{-19}	-
T_C	temperature	-	C
p_b	starting pressure at the lower bound of the atmospheric layer	101325	pa
b	atmospheric layer coefficient	0	-
$T_{m,b}$	standard Temperature	288.15	K
$L_{m,b}$	temperature change rate with height	-6.5	K/km
H	altitude	-	m
H_b	altitude of the bottom of the atmospheric layer	0	m

g	gravitational constant	9.80665	m/sec^2
M	molecular weight of dry air	28.9644	gm/mol
R	gas constant	8.31432	J/ mol*deg K
n	number of data points	-	-
i	index of particular data point	-	-
$v(i)$	MET value at a index	-	-
t	time	-	s
$v(t)$	value at a particular time	-	-
μ_s	The mean error in a sensor's reading value	0	-
σ_s	The standard deviation in a sensor's reading value	-	-
$Error(\mu_s, \sigma_s)$	A sample error using a particular mean and standard deviation	-	-

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(U)Paper submission of *The Improvement in Performance a Ground Combat Vehicle Could Expect From the Use of a Real Time MET Sensor*

(U) Purpose

(U) This ARDEC Technology Protection Note provides ARDEC information pertinent to the abstract submittal of *The Improvement in Performance a Ground Combat Vehicle Could Expect From the Use of a Real Time MET Sensor*.

(U) Discussion

(U) Various meteorological conditions affect the performance and accuracy of weapons. ARDEC investigated the use of commercially available meteorological sensors and their effect on the accuracy of weapons.

(U) Analyst Comment

(U//FOUO) As a result of this process the analyst concludes that there is no PCPI present in this document. The sensors are commercially available and the equations used are basic science.

(U//FOUO) The document is properly marked.

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